

# The CTIO Prime Focus CCD: System Characteristics from 1982-1988

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RUNNING HEAD: The PFCCD System at CTIO

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## ABSTRACT

The CTIO Prime Focus CCD instrument with an RCA CCD was in operation at the CTIO 4-m telescope for six years between 1982-1988. A large body of literature has been published based on CCD images taken with this instrument. We review the general properties of the now-retired PFCCD system to aid astronomers in the interpretation of the photometric data in the literature.

## 1. Introduction

In October 1982 the KPNO prime focus CCD system (PFCCD) was transferred to CTIO. For six years, until de-commissioning in mid-1988, RCA #1 CCD was the only CCD available for direct imaging at the 4-m telescope. The system is described by Marcus et al. (1979), Goad (1980), and McGuire (1983), while from a more astronomical perspective the faint galaxy study by Tyson and Seitzer (1988) is recommended.

The detector is an RCA type SID52501 CCD, designed for use in high speed (several Mpixel/second) 525-line TV applications. The format is 320 x 512 pixels, each 1.2 mil ( $30.48\mu$ ) square with no dead bands. It is a thinned, back-illuminated device, with a silicon monoxide anti-reflection coating. The back surface is doped to prevent recombination near the surface, which improves the ultraviolet and blue response. The CCD is bonded to a 0.5mm-thick glass substrate, the front surface of which is anti-reflection coated with magnesium fluoride. The device data sheet and U.S patent no. 4266334 (May 12 1981) can be consulted for further details. No definitive description of the RCA CCD's has ever appeared in the literature.

This type of RCA CCD is known as a "first generation" RCA CCD, and has the general characteristics of high readout noise (at least 70 electrons) and poor vertical (parallel) charge

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transfer at very low light levels. The output amplifier emits light during readout. Since RCA #1 was used exclusively at the CTIO 4-m prime focus, these defects were of little importance for broad-band (eg *BVRI*) imaging. The “second (and final) generation” of RCA CCD’s employed at CTIO has 40 electrons readout noise, better low level charge transfer, but a higher radiation event rate resulting from a change in the glass substate material.

The CCD controller has been described in detail elsewhere (see above references). It incorporates a temperature controller set to  $-105^{\circ}\text{C}$ , which results in a dark rate of approximately 70 electrons  $\text{pixel}^{-1} \text{ hr}^{-1}$  when sampled well away from the glowing output amplifier. The CCD output was digitized to 15 bits, at a gain of 10.1 electrons per digital unit. The data were written as 16-bit unsigned integers. The 352 (320 CCD, 32 overscan)  $\times$  512 pixel raw images required 8 seconds for readout, with a noise of 85 electrons  $\text{pixel}^{-1}$  rms (root-mean-square). During the normal on-site processing of bias subtraction and flat-field division, it was normal to trim off several of the bright left-hand columns. The control computer was originally a PDP 11/23 with 256K memory, 77 MB Winchester disk, and a 1600 bpi 9-track magnetic tape drive.

Apart from the low level charge transfer problem, many tests over the several years of use at CTIO demonstrated that RCA #1 was linear to  $\sim 0.5\%$  or better over the full range of the ADC, and saturation did not occur until  $\sim 400,000$  electrons.

The PFCCD system viewed a  $3' \times 5'$  field roughly  $6.5'$  west of the telescope optical axis, with the long axis oriented east-west. The PFCCD was used with the 4-m telescope doublet corrector, which is made of fused silica with magnesium fluoride anti-reflection coatings. This corrector covers a field diameter of  $17'$ . Ray tracings show that at the (off-axis) position of the CCD the corrector produces images with 0.4 arcsec 75% enclosed energy. Qualitatively, these images have tight cores and low-level wings, with little variation as a function of wavelength. The image scale with RCA CCD is  $0.59 \pm 0.01$  arcsec/pixel, corresponding to  $19.3 \pm 0.3$  arcsec/mm.

The first light of the instrument at CTIO was the night of 6 April 1982. The first scheduled run went to P. Seitzer and H. Butcher, which started on 12 April 1982. The last scheduled run with the RCA #1 CCD PFCCD was 25 March 1988. Roughly 180 runs on 440 nights were scheduled with this instrument. About 25% of the observer time on the 4-m telescope (not used for engineering purposes) went to the PFCCD during this period. The most popular use of the instrument was broad-band imaging in a subset of the *UBVRI* Johnson and Kron-Cousins photometric systems. While the PFCCD was quite powerful for broad-band imaging where sky-limited exposures were achieved in a few minutes, the very high readout noise of the CCD made this system less attractive for narrow-band imaging.

In this short contribution, we record transmission measurements for the most popular *UBVRI* filters used in by the PFCCD, together with quantum efficiency measurements for RCA #1. The latter measurement will be useful for those astronomers trying to reconstruct photometric color terms for non-standard filters. In addition, these tables in conjunction with spectrophotometric atlases of standard stellar spectra (see for example, Massey et al. 1988, Massey and Gronwall

1990, Hamuy et al. 1992, 1994) can be used to study the effects of non-stellar flux distributions on the transformation of natural to standard photometric systems. It is well-known that non-stellar flux distributions can lead to systematic errors in the transformed photometry. For instance, Suntzeff et al (1988) found systematic differences of up to 0.4 magnitudes in the  $I$  magnitude of SN1987A that were explained by slight differences in the  $I$  filter convolved with the supernova flux distribution (Bessell 1983, Menzies 1989).

## 2. $UBV(RI)_C$ Filter Transmissions

The original  $BVRI$  filters used with the PFCCD system were a set of interference filters obtained as part of a bulk order organized by J. Mould, then at KPNO. Two sets were allocated to the PFCCD, one as spare. The interference  $BV$  filters were rarely used. Instead, a set of glass filters locally known as “CTIO glass set #2” was used. On 75% of the PFCCD runs, the #2  $BV$  glass set was installed.

The CTIO glass set #2  $BV$  filters are 2x2 inch square filters, 4mm thick, and cemented with lens bond M62. The filter recipes are:  $B$ , BG12/1mm + GG385/2mm + BG18/1mm; and  $V$ , GG495/2mm + BG18/2mm. The  $B$  filter is identical to the  $B$  filter recommended (for photocathodes) by Bessell (1979), and the  $V$  is very similar to his  $V$  filter. Some astronomers referred to the CTIO glass set #2  $BV$  filters as the “Bessell” set, although this is only strictly true for the  $B$  filter. The interference  $(RI)_C$  set was generally known as the  $R34$  and  $I34$  filters or the “Mould” set. The filters in this set are 2x2 inches and 3mm thick.

The 2x2 inch  $U$  filters were less standard. The original  $U$  filter was a 4mm thick filter with the recipe: UG2/1mm + BG38/1mm + WG295/2mm. Because it suffered from red-leak, in 1984 an interference  $U$  filter was purchased. This was locally called the “ $U_{CTIO}$ -new” filter or the “3650Å/600Å” filter, and was 6mm thick. The filter only had 35% peak transmission, and in late 1985, this filter was replaced by a  $U$  filter made from a 1mm UG2 glass filter bonded to an optical cell containing copper sulfate (80%) solution, as recommended by Bessell (1976). This final filter had three times the throughput of the interference filter. The filter was 9.3mm thick. Three of these filters were made by D. Hamilton for use at CTIO. They are locally known as the “ $U$ -Hamilton” filters. Users of this or any other liquid cell  $U$  filter should note the warning in Bessell (1976) that this type of cell can drastically change its transmissivity through very small levels of ferric ion contamination.

The  $UBV(RI)_C$  filters were measured in the Optics Laboratory on Cerro Tololo. A double pass Oriel spectrometer feeds near monochromatic light at  $f/13.5$  through the filter and then to either an S-5 or S-1 photomultiplier, depending on the wavelength range to be measured. At each wavelength both the filter and the “straight-through” response are measured.

The transmission curves for the #2  $BV$  glass set were measured in 1980 and 1989. These curves are plotted in Figure 1 and the 1989 curves are given in Table 1. The figure shows that

there has been little change in the transmissivity properties of this set over a 9-year period.

The transmission curves for the *RI34* set were measured in 1983 and 1989. In addition, we also have a curve for *R34* from 1987. These curves are plotted in Figure 2 and the the 1989 curve is given in Table 2. Note in this case there was a small shift in the transmission region of the interference filters, especially in *I34*.

The *U* transmission curves are plotted in Figure 3. In the left panel we show the *U*-Hamilton #1 filter as measured in 1986 and 1989. In the right panel we show the “*U*<sub>CTIO-new</sub>” interference filter as measured in 1984 and 1989. Both filters remained quite stable during these time periods. The 1989 curves are given in Table 3.

### 2.1. Some comments on color terms

Most users of the PFCCD system relied on the *UBV(RI)<sub>C</sub>* standard star lists of Landolt (1973, 1983, 1992) and Graham (1982). There is a useful extension of some of the Landolt fields in Stetson and Harris (1988). These fields are suited for CCD photometry since more than one standard can be fit on a frame. Careful observers also chose stars from Menzies et al. (1989) as well as Graham (1982) to include some stars that culminate between airmass 1.0 and 1.2, which are missing from the equatorial Landolt lists.

The bright limit for 1 second exposures was about  $V = 9.6$  for the PFCCD system. Exposures this short must be corrected for the shutter timing errors. The actual time the shutter was open was  $t + \delta$  where  $\delta$  was 10ms.

A large number of papers have been published based on the PFCCD photometry, mostly in the *BV* system. A number of these papers have presented the color transformations from the natural to standard system (e.g. Aaronson et al. 1984, Da Costa 1985, Smith et al. 1986, Hesser et al. 1987, McClure et al. 1987, Bolte 1987). Most of the papers solve for a linear color transformation in the “traditional” form of  $M = M(m_0, c_0)$  where  $M$  is the transformed magnitude or color in the standard system, while  $m_0$  and  $c_0$  are the observed magnitude and color on the natural system corrected for extinction (Hardie 1962). For 11 different runs between 1982 and 1987, we find the following mean linear color transformations:

$$V = a + v_0 - 0.013(\pm 0.011)(b - v)_0$$

$$B - V = b + 1.092(\pm 0.018)(b - v)_0$$

where the error listed is the standard deviation (not mean error) of the 11 values. It is our experience, and is verified by Stetson et al. (1989) that the *BV* transformations are non-linear if very red stars are included. We recommend the transformation scheme suggested by Harris et al. (1981) and Stetson and Harris (1988) where the non-linear transformation is written as

$m = m(M, C, X, \dots)$  where  $M$  and  $C$  are the standard colors,  $X$  is the airmass, and  $m$  is the observed magnitude. These techniques also allow the observer to solve for color terms on nights of thin cirrus, or include data where only a single filter was employed.

### 3. Quantum Efficiency of RCA #1

The quantum efficiency of CTIO CCD RCA #1 was measured with respect to a calibrated photo-diode using an apparatus (R2D2) designed at CTIO by Dr B. Atwood. In this apparatus, an Oriel spectrophotometer feeds a monochromatic beam along a fiber-optic cable, into an integrating sphere which, via relay lenses and a beam-splitter, focuses the light onto both the calibrated diode and the CCD. Measurements of relative sensitivity of the CCD and diode are made as a function of wavelength, usually at 100Å intervals. The resolution, governed by the slit width, is normally set to 50Å. The CCD and photo-diode are then interchanged with respect to the incoming beam and a second series of measurements taken. The two sets of measurements can then be combined in order to remove instrumental effects. A deuterium lamp, ultraviolet fiber (fused silica) and ultraviolet - integrating sphere are normally used for the 3000 - 4500Å wavelength region. A quartz lamp is used for the region 4000 - 10000Å, with its own integrating sphere which is fed by a trifurcated fiber cable in order to improve the evenness of illumination. All measurements are made in the first order of the grating, with a long pass filter inserted to block the second order for measurements at wavelengths longer than 6000Å. Control of the spectrometer and recording of data proceeds automatically under computer control.

Repeated measurements give us confidence that the *relative* quantum efficiencies measured using R2D2 are accurate to better than 2%. However we prefer to be conservative with respect to the overall *absolute* scale, and will assign an error of 10%, even though R2D2 is designed to eliminate sources of systematic error as much as possible. We find that the absolute peak quantum efficiency of RCA #1 is somewhere in the range 57 - 69%. The quantum efficiency of RCA #1 is plotted in Figure 4 and listed in Table 4.

The shape of the spectral response for RCA CCD's depended critically on the amount of thinning. Generally, "second generation" devices were not thinned as much as the "first generation" CCD's and consequently have poorer response in the ultraviolet but better red response. However the degree of thinning during manufacture was evidently not well controlled and some "first generation" devices also had poor ultraviolet response. RCA #1 has just the opposite; excellent ultraviolet but poor red response. It was also renowned for the strength of the fringes seen when illuminated monochromatically, such as from night sky emission lines when imaging in the V, R and I bands. These fringes are stronger the thinner the CCD, at least for the RCA CCD's.

#### 4. Other comments

While the filter transmission and CCD quantum efficiency dominate the final throughput curve for the system, there are some other effects that will modify the final number of detected photons per spectral element. Besides the obvious case of interstellar extinction (see Cardelli et al. 1989 for a particularly convenient form of this law) and atmospheric extinction (an average law for CTIO is given by Gutierrez-Moreno et al. 1986), light will be attenuated by the aluminum reflection from the primary mirror and the passage through the doublet corrector. The reflectivity of aluminum is conveniently summarized by Smith, et al (1985) but it should be noted that this curve is for an idealized, fresh aluminum surface. A plot of the mirror reflectivity for the freshly aluminized Canada-France-Hawaii Telescope mirror is given by Magrath (1994). The reflectivity of fresh aluminum is very high and uniform throughout the optical, except for an interband absorption feature at about 8500Å which is about 1500Å wide with a maximum absorption of about 10%.

We have laboratory information on the transmissivity of the prime focus corrector, which is a fused silica, air spaced doublet system. The glass transmissivity of the elements, however, is expected to be flat throughout the optical.

A common point of confusion for observers with the old PFCCD system was the coordinate center for the CCD image. In almost all cases, the coordinates written in the header of the image referred to position of the telescope optical axis, and *not* the CCD position. The true CCD position was  $\sim 6.5'$  west of the telescope optical axis - that is, one must subtract 6.5' (in units of RA) from the headers stored in the images to recover the CCD center. In a few cases, the observers re-zeroed the telescope pointing to the CCD center, but this was not recommended because the telescope pointing model would be less accurate.

We wish to thank Dr. Ivan King for urging the publication of the basic characteristics of the CTIO PFCCD system. We would like to thank R. Gonzalez and G. Martin for measuring the filter responses. We thank P. Stetson, G. Da Costa, M. Bolte, and M. Dickinson for communicating their experience with the PFCCD system. G. Jacoby provided the ray tracings for the doublet corrector. We thank B. Magrath for providing information on aluminum reflectivities.

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Fig. 1.— Transmission curves for the CTIO glass set #2 *BV* filters. The dashed line represents the filter transmission for 1980, and the solid line for 1989. Note the constancy of the curves, as would be expected for glass filters.

Fig. 2.— Transmission curves for the *RI34* interference filter set. The dashed line represents the filter transmission for 1983, and the solid line for 1989. An additional curve from 1987 is plotted for *R34* as a dotted line. Note the small changes in the curves, especially for *I34*.

Fig. 3.— Transmission curves for the *U* filters. The left panel shows the curves for the “*U*-Hamilton” filters, which are the most used *U* filters on the PFCCD system. The dashed curve represents the filter transmission in 1986, and the solid curve in 1989. The right panel shows the curves for the “*U*<sub>CTIO-new</sub>” interference filter. The dashed curve represents the filter transmission in 1984, and the solid curve in 1989.

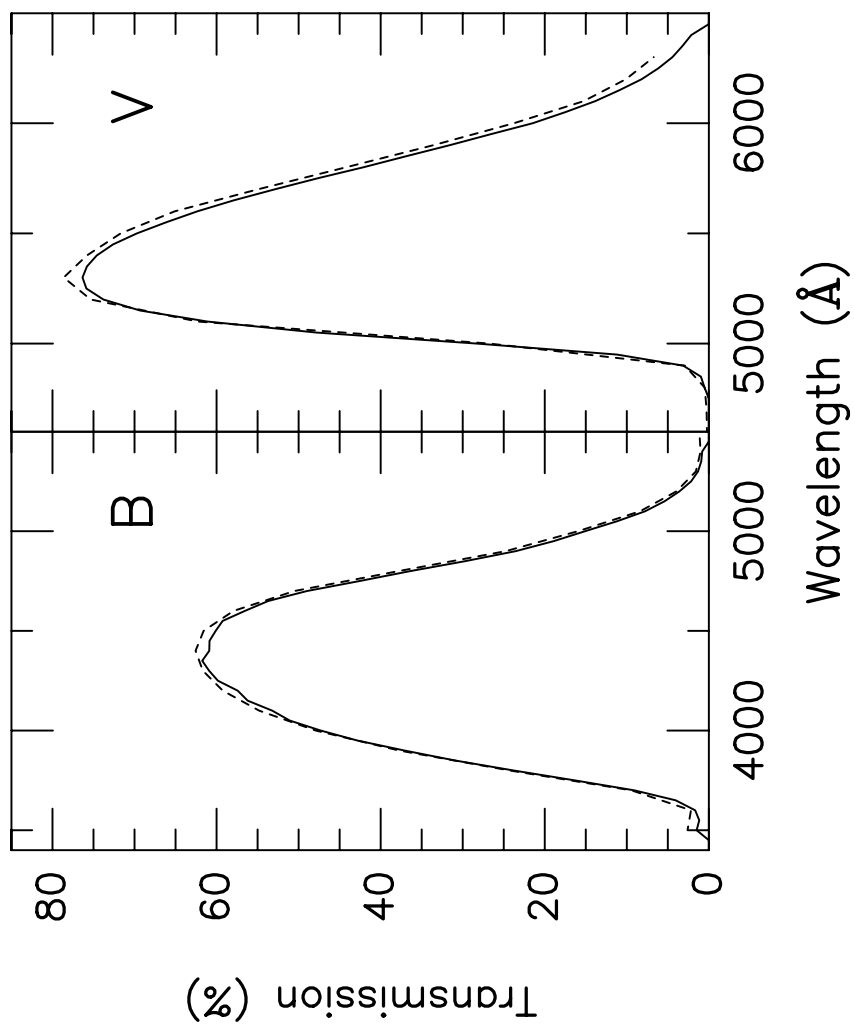
Fig. 4.— The quantum efficiency curve for the RCA CCD #1, which was used in the PFCCD system from 1982-88.

TABLE 1. Transmission Curves for #2 *BV* CTIO Glass Filter Set

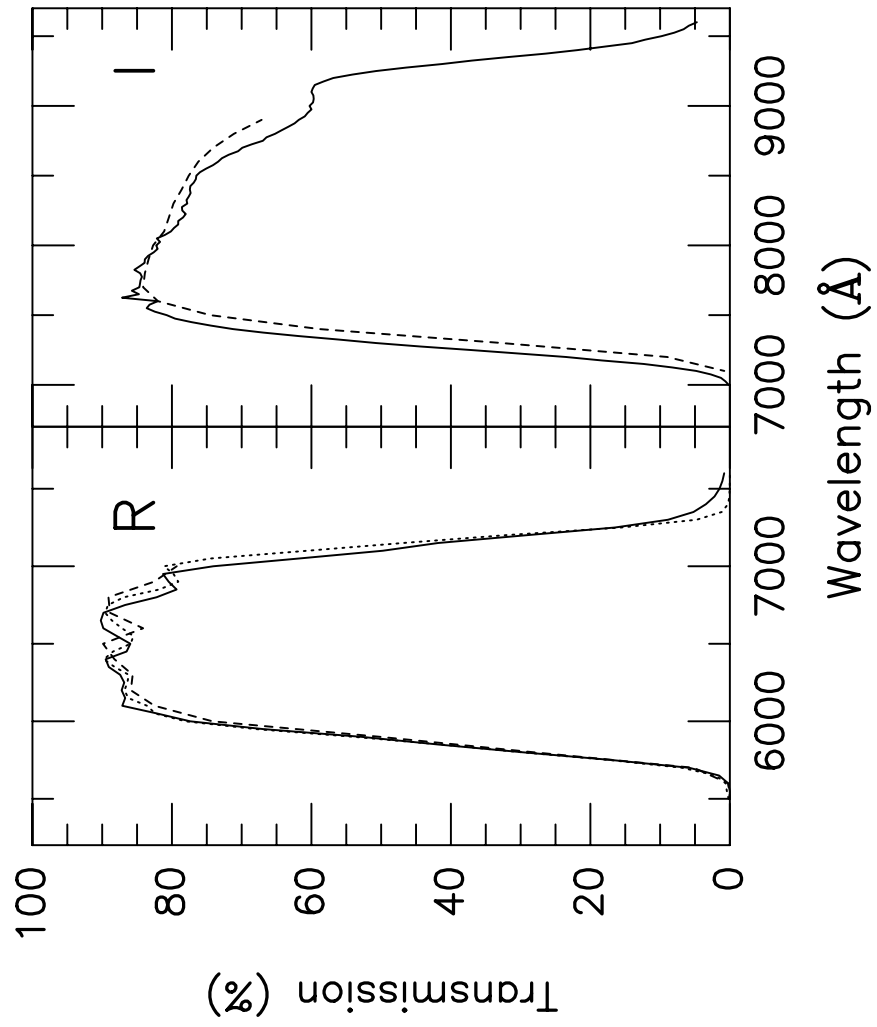
TABLE 2. Transmission Curves for *RI34* CTIO Interference Filter Set

TABLE 3. Transmission Curves for CTIO *U* Filters

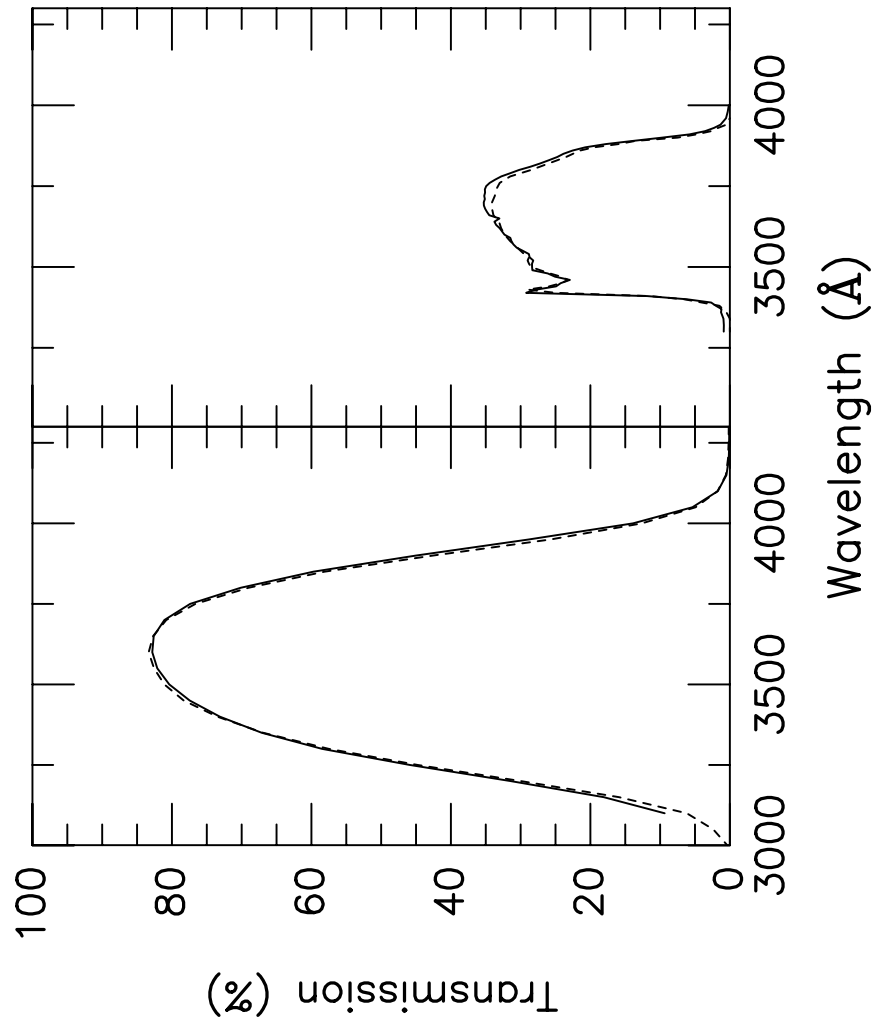
TABLE 4. Quantum Efficiency Curve for RCA #1 CCD



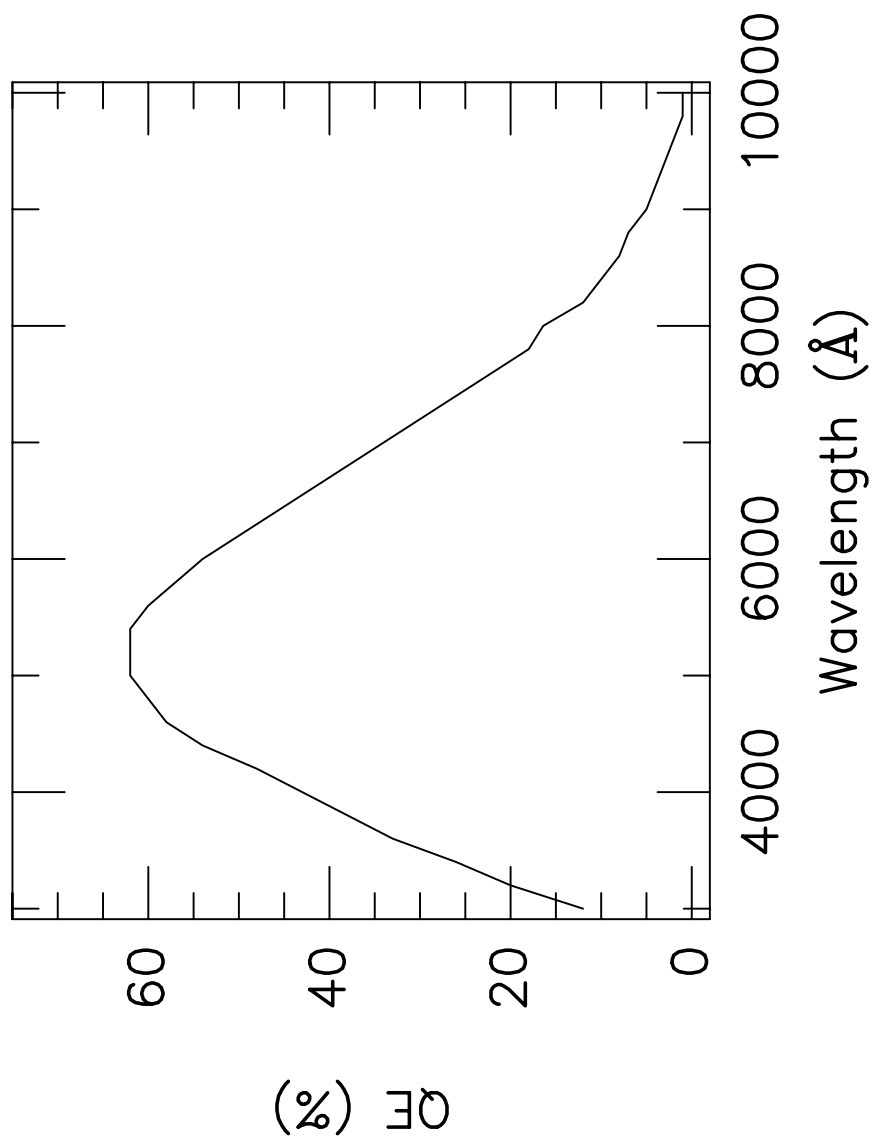
Suntzeff and Walker. Figure 1



Suntzeff and Walker. Figure 2



Suntzeff and Walker. Figure 3



Suntzeff and Walker. Figure 4



TABLE 1. Transmission Curves for #2 *BV* CTIO Glass Filter Set

Wavelength (Å)	T (%)	Wavelength (Å)	T (%)	Wavelength (Å)	T (%)	Wavelength (Å)	T (%)
<i>B</i> filter							
3450	0.	4000	47.3	4550	59.3	5100	7.8
3500	1.5	4050	51.1	4600	56.6	5150	5.4
3550	1.2	4100	53.2	4650	53.7	5200	3.6
3600	1.7	4150	56.2	4700	49.0	5250	2.2
3650	4.0	4200	57.4	4750	42.6	5300	1.3
3700	9.1	4250	59.8	4800	36.4	5350	0.9
3750	16.3	4300	60.9	4850	29.7	5400	0.8
3800	23.8	4350	61.8	4900	23.5	5450	0.
3850	31.0	4400	60.9	4950	18.9		
3900	37.1	4450	60.9	5000	15.1		
3950	42.8	4500	60.1	5050	11.2		
<i>V</i> filter							
4750	0.	5200	73.8	5650	57.9	6100	13.9
4800	0.5	5250	75.9	5700	52.9	6150	10.9
4850	1.0	5300	76.3	5750	47.7	6200	8.2
4900	3.1	5350	75.8	5800	42.1	6250	6.1
4950	11.1	5400	74.6	5850	36.9	6300	4.4
5000	28.3	5450	72.6	5900	31.6	6350	3.2
5050	47.8	5500	69.7	5950	26.6	6400	2.1
5100	61.1	5550	66.2	6000	21.5	6450	0.
5150	69.3	5600	62.4	6050	17.5		



TABLE 2. Transmission Curves for *RI34* CTIO Interference Filter Set

Wavelength (Å)	T (%)	Wavelength (Å)	T (%)	Wavelength (Å)	T (%)	Wavelength (Å)	T (%)
<i>R34</i> filter							
5550	0.	6100	87.1	6650	90.2	7200	29.2
5600	0.2	6150	86.7	6700	89.8	7250	16.5
5650	1.5	6200	87.2	6750	86.7	7300	8.9
5700	5.8	6250	86.8	6800	82.2	7350	5.2
5750	16.9	6300	87.4	6850	79.3	7400	3.4
5800	29.7	6350	89.1	6900	80.5	7450	2.2
5850	41.8	6400	89.5	6950	81.3	7500	1.5
5900	52.9	6450	86.5	7000	74.1	7550	1.1
5950	67.0	6500	86.0	7050	61.8	7600	0.8
6000	77.4	6550	87.9	7100	49.8		
6050	82.1	6600	89.8	7150	41.8		
<i>I34</i> filter							
7000	0.2	7675	85.8	8350	77.6	9025	59.8
7025	0.6	7700	84.7	8375	77.3	9050	59.7
7050	1.3	7725	84.6	8400	77.4	9075	59.7
7075	2.7	7750	84.5	8425	77.4	9100	60.0
7100	4.8	7775	84.3	8450	76.9	9125	59.8
7125	8.3	7800	84.6	8475	76.6	9150	59.5
7150	12.4	7825	85.4	8500	76.5	9175	58.3
7175	18.3	7850	84.6	8525	76.0	9200	56.9
7200	23.5	7875	83.9	8550	75.1	9225	54.1
7225	30.3	7900	83.9	8575	74.1	9250	50.7
7250	37.2	7925	83.4	8600	73.4	9275	46.4
7275	44.3	7950	82.6	8625	72.8	9300	41.3
7300	50.8	7975	82.0	8650	71.8	9325	37.0
7325	56.1	8000	82.2	8675	70.5	9350	31.9
7350	61.8	8025	81.7	8700	69.9	9375	26.4
7375	66.9	8050	82.2	8725	68.5	9400	21.9
7400	71.2	8075	81.0	8750	67.0	9425	18.0
7425	74.4	8100	80.2	8775	66.4	9450	14.0
7450	77.2	8125	79.7	8800	65.2	9475	12.1
7475	79.6	8150	79.1	8825	64.3	9500	9.8
7500	80.8	8175	79.1	8850	63.3	9525	8.0
7525	82.5	8200	78.4	8875	62.4	9550	6.6
7550	83.6	8225	78.0	8900	61.8	9575	5.9
7575	83.2	8250	78.5	8925	61.0	9600	4.7
7600	82.0	8275	78.6	8950	60.5		
7625	87.2	8300	77.8	8975	60.0		
7650	84.7	8325	77.9	9000	60.3		

TABLE 3. Transmission Curves for CTIO *U* Filters

Wavelength (Å)	T (%)	Wavelength (Å)	T (%)
<i>U</i> -Hamilton #1 Filter			
3000	0.3	3800	69.0
3050	2.4	3850	58.1
3100	6.2	3900	42.6
3150	15.9	3950	25.7
3200	30.0	4000	12.6
3250	44.8	4050	4.9
3300	57.5	4100	1.8
3350	66.9	4150	0.6
3400	73.5	4200	0.3
3450	78.3	4250	0.2
3500	81.1	4300	0.2
3550	82.6	4350	0.2
3600	83.3	4400	0.2
3650	82.7	4450	0.1
3700	80.8	4500	0.
3750	76.6		
<i>U</i> -new Interference Filter			
3300	0.9	3700	35.3
3350	1.1	3750	34.9
3400	6.1	3800	30.2
3450	24.2	3850	23.9
3500	28.4	3900	9.7
3550	29.7	3940	0.8
3600	32.3	4000	0.2
3650	33.0		

TABLE 4. Quantum Efficiency Curve for RCA #1 CCD

Wavelength (Å)	QE (%)	Wavelength (Å)	QE (%)	Wavelength (Å)	QE (%)	Wavelength (Å)	QE (%)
3000	12	4800	60	6600	42	8400	10
3200	20	5000	62	6800	38	8600	8
3400	26	5200	62	7000	34	8800	7
3600	33	5400	62	7200	30	9000	5
3800	38	5600	60	7400	26	9200	4
4000	43	5800	57	7600	22	9400	3
4200	48	6000	54	7800	18	9600	2
4400	54	6200	50	8000	16	9800	1
4600	58	6400	46	8200	12	10000	1